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# An experimental investigation of the cyclic response of bucket foundations in soft clay under one-way cyclic horizontal loads

Le Chi Hung[a,b,1], Si-Hoon Lee[c], Ssenyondo Vicent[d], Sung-Ryul Kim[e,*]

[a] Department of Civil Engineering, National University of Ireland Galway, Ireland
[b] School of Physics, National University of Ireland Galway, Ireland
[c] Rhehwa Engineering Co., Ltd., Centum dong-ro, Haeundae-gu, Busan, South Korea
[d] Department of Civil Engineering, Dong-A University, 840 Hadan2-dong, Saha-gu, Busan, South Korea
[e] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, South Korea

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ABSTRACT

This study conducted 1 *g* laboratory tests to investigate the accumulated rotation and unloading stiffness of two model bucket foundations embedded in soft clay under one-way cyclic horizontal loads. The model bucket foundations were specifically designed to have embedment ratios of 0.5 and 1. Ground models were prepared by consolidating the kaolin slurry. One-way cyclic horizontal loads of up to $10^4$ cycles were applied varying loading magnitudes. Test results showed that the accumulated rotations of the bucket foundations increased with increased number of load cycles and cyclic horizontal load magnitudes. The unloading stiffness of the bucket foundations increased with increasing number of cycles and embedment ratios but decreased with increasing cyclic horizontal load magnitude. Based on the model test results, empirical equations were proposed to evaluate the accumulated rotation and unloading stiffness of the bucket foundations in soft clay under one-way cyclic horizontal loads.



## 1. Introduction

A bucket foundation consists of a circular top-lid reinforced by a cylindrical skirt around its circumference. The bucket foundations have been extensively used in offshore facilities, such as platforms, and jacket structures [29,4,14,20]. The bucket foundation has been recently used as an alternative foundation for offshore wind turbines because of several advantages, such as low cost, easy installation, and ability to provide a high-resistance against overturning moment.

The behavior of bucket foundations under static loading in clay has been extensively investigated. Most works have been performed using finite element (FE) analysis [30,12,5,15,16]. A few physical tests were conducted to study the behavior of the bucket foundations under static and cyclic vertical loads [32,31,22].

A critical design issue for offshore wind turbines would be the accumulated rotation of the foundation under cyclic horizontal load [39]. Several studies have investigated the behavior of bucket foundations in sand under horizontal cyclic loading (e.g. [6,39,10,8]. They found that the accumulated displacement or rotation of bucket foundations increased with the increase in number of load cycles. To our knowledge, no study has been conducted on the accumulated rotation of bucket foundations in soft clay under long-term cyclic horizontal loads.

Wang et al. [36] investigated cyclic bearing capacity of the single bucket foundation in undrained clay using the long-term cyclic triaxial test and finite element analysis. The cyclic triaxial test was performed up to $10^4$ cycles. From the test results, they found that the accumulated strain increased with the increase in the number of stress cycle and the cyclic stress magnitude. The accumulated strain become significant at the cyclic stress that is larger than 0.5 time the failure stress. A pseudo-static elasto plastic failure criterion was suggested to determine the vertical and horizontal cyclic bearing capacities of the single bucket foundation, as these cyclic bearing capacities are important parts in design of the bucket foundation in clay

This paper presents the results from a series of 1 *g* experimental tests on two model bucket foundations with embedment ratios of $L/D = 0.5$ and 1 (where $D$ is the foundation diameter, and $L$ is the skirt length). The accumulated rotations and unloading stiffness of the bucket foundations in soft clay were investigated under long-term cyclic horizontal load. The number of load cycles $N$ of up to $10^4$ cycles was applied varying load magnitudes.

* Corresponding author.
*E-mail address:* sungryul@snu.ac.kr (S.-R. Kim).
[1] Formerly Dong-A University.

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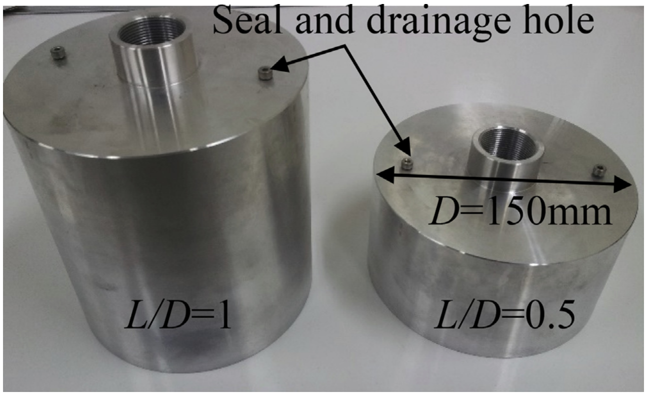


**Fig. 1.** Photos of bucket foundations used in this study.

**Table 1**
Geometrical parameters of the prototype buckets and bucket models.

| Item | Prototype (m) | Model (m) |
|---|---|---|
| Diameter | $D_p = 15$ | $D_m = 0.15$ |
| Skirt length | $L_p = 7.5$ and 15 | $L_m = 0.075$ and 0.15 |
| Skirt thickness | $t_p = 0.033$ | $t_m = 0.001$ |
| Top lid thickness | Reinforcement | 0.005 |

## 2. Model tests

### 2.1. Bucket foundation models and test programs

Fig. 1 shows photos of bucket foundation models used in this study. The prototype foundation had an outer diameter of 15 m and a skirt thickness of $t_p = 33$ mm, and two skirt lengths $L_p$ of 7.5 m and 15 m were considered. The Young's modulus of steel was set to 210 GPa.

The bucket foundation models were designed by considering a length scale ratio of 1:100 [39]. The dimension of the bucket foundation model was calculated using the scaling law presented in the work of Wood [37] for laboratory test at single gravity (1*g*). The bucket models were fabricated from aluminum that had Young's modulus of 70 GPa.

To satisfy the scaling law of bending stiffness ($E \times I$, where $E$ is Young's modulus and $I$ is the cross-sectional inertia) between the bucket models and prototypes, the skirt thickness of the bucket models was calculated as 0.01 mm. However, the skirt thickness of the bucket models was made as 1 mm, as this thickness is the minimum value that can be fabricated. This thickness was higher than the actual scaled thickness. Therefore, the structural deformation along the skirt of the bucket foundation model might not occur during loading.

The top-lid thickness was intentionally set to 5 mm to simulate the reinforcement at the top-lid, which will prevent any possible deformation at the connection between the tower and the top-lid. This assumption was confirmed using finite element analysis. The geometrical parameters of the prototype bucket and the bucket models are presented in Table 1.

Two different drainage holes were made on the lid of the foundation to allow the water to come out during the foundation's installation process. The holes were immediately closed before a test began. At the center of the lid, a threaded hole was attached to connect the foundation with a tower. The weight of the tower was 10N. This tower weight was fabricated after applying the length scaling ratio of 1:100 to represent a vertical weight of approximately 10 MN, which is typical for a 5 MW offshore wind turbine [1].

The magnitude of the horizontal loads and horizontal displacements of the bucket foundations were measured using a load cell and two LVDTs, respectively. These horizontal loads and displacements were recorded through a command program designed with LabVIEW 2012.

A test program was designed to investigate the accumulated rotation and unloading stiffness of the two bucket foundations at $L/D = 0.5$ and 1 under one-way cyclic horizontal loads. A total of 8 tests were required to complete the test program. Two static horizontal load tests were first carried out to determine the horizontal failure loads ($Ho$) of the bucket foundations. Different one-way cyclic horizontal load magnitudes $H_c$ of each foundation were then determined according to the cyclic load ratio of $R_c = H_c/Ho$ (Table 2).

### 2.2. Model ground preparation

Fig. 2 shows a detailed diagram of the soil box with slurry, loading and drainage systems. The soil box was made of an acrylic material with 700 mm height, 750 mm length, and 500 mm width. The optimum soil box size was determined by performing FE analyses to minimize the boundary effect of the box. The box had a 15mm-thick wall, surrounded and reinforced by thick acrylic and steel frames to avoid any possible expansion.

Clay ground was prepared by consolidating a kaolin slurry. The slurry had an initial water content $w_i$ of approximately 126%, which was approximate twice the liquid limit ($LL = 63\%$) following the suggestions of previous works e.g. [23,24]. The uniform kaolin slurry was carefully made by controlling the required volume of water and kaolin powder and mixing in a large volume mixer during 2 h in each batch.

The drainage system was simply built with 30 mm thick compacted sand layers located at the bottom and the top of the slurry. A geotextile filter sheet was laid between the sand layer and slurry to prevent sand from being embedded into the slurry. Plastic tubes linked the bottom, and top sand layers to (*1*) circulate the water drained from the bottom of the clay ground during consolidation process, and (*2*) to make the head equivalent between the top and bottom of clay ground during consolidation.

A 1.5 cm-thick acrylic loading plate with drainage holes was placed on the top sand layer to uniformity distribute load during consolidation. Approximately 10 mm of water was kept above the surface of this plate during consolidation.

Consolidation processes were then carried out to prepare the soft clay with the target water content. The consolidation stresses were primarily obtained by performing two incremental loading for the end of primary consolidation tests for the same slurry at the same initial water content ($w_i \approx 126\%$). Consolidation stresses were adapted and modified from the work of Hong et al. [13], in which the loading increments were 0.5 kPa, 1.5 kPa, 2.5 kPa, 3.5 kPa, 5.5 kPa, 7.5 kPa, 10 kPa, 20 kPa, 40 kPa, and 80 kPa. The consolidation coefficient values $c_v$ of the clay were 2.0805 m$^2$/day, 0.0183 m$^2$/day and 0.028 m$^2$/day for the consolidation pressure of 10 kPa, 20 kPa and 40 kPa, respectively. A maximum consolidation stress of 20 kPa was applied to make clay grounds. Approximately five weeks of consolidation time were required to obtain clay with a target water content of approximately $w_n \approx 80\%$. After consolidation and before each test, the top sand layer and the 10 mm-thick of clay ground surface were removed. A total of eight soil boxes were prepared.

Soil properties were immediately investigated after each model test was completed. The $w_n$ values of clay grounds were measured for three different soil boxes by taking the clay at different excavating depths. The $w_n$ values were slightly decreased with depth, as shown in Fig. 3(a). Fig. 3(b) shows the effective unit weight of soil, calculated from the $w_n$ values. The undrained shear strength $s_u$ of clay grounds was investigated by using a digital miniature static cone penetrometer (CPT) model HS-4210, made by Humboldt Mfg.